GROUND-MARITIME STRUCTURE INTERACTION. RECENT FAILURES IN INNER GRAVITY CONSTRUCTIONS ON THE SPANISH COASTLINE*

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Abstract　A maritime construction is usually a slender line in the ocean. It is usual to see just its narrow surface strip and not analyse the large amount of submerged material the latter is supporting. Without doubt, it is the ground to which a notable load is transmitted in an environment subjected to periodic, alternating stresses, dynamic forces which the sea's media constitute.

Both an outer and inner maritime construction works in a complex fashion. A granular solid(breakwater) breathes with the incident wave flow, dissipating part of the wave energy between its gaps. The backflow tries to extract the different items from the solid block, setting a balance between effective and neutral tensions that follow Terzaghui's principle.

On some occasions, fluidification of the armour layer has caused the breakwater to collapse(Sines, Portugal, February 1978). On others, siphoning or liquefaction of sand supporting monoliths(vertical breakwaters) lead them to destruction or collapse(New Barcelona Harbour Mouth, Spain, November 2001).

This is why the ground-force-structure interaction is a complicated analysis with joint design tools still in an incipient state.

The purpose of this article is to describe two singular failures in inner maritime constructions in Spain deriving from ground problems (Malaga, July 2004and Barcelona, January 2007). They occurred recently and the causes are the subject of reflection and analysis.

Key words　Ground-Maritime structure, Interaction, failure, Coastline, Spain

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地基与海洋建筑物相互作用——以最近西班牙海岸线建筑物内部损坏为例

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摘　要　海洋工程通常是一个细长的线。我们通常看到的仅仅是建筑物狭长的表面,而不分析支撑他们的大量水下材料。毋庸置疑,海底地基将承受来自于海洋的周期性和交替的静力以及变化的动力。

外部和内部的海上工程均在复杂的环境中运行。固态颗粒(防波堤)可以吸入入射水流,并且通过颗粒之间的间距吸收海浪的能量。回流试图从固态颗粒中抽离物质,这样一个遵从太沙基原理的基于有效拉力和中性拉力之间的平衡建立起来。

在某些情况下,防护层的液化已经造成了防波堤崩溃(Sines,葡萄牙,1978 年 2 月)。在其他情况下,虹吸作用或液化导致巨石(垂直的防波堤)毁坏或崩溃(新巴塞罗那港口,西班牙,2001 年 11 月)。

结合复合设计工具的地基-作用力——结构相互作用的过程是一个复杂的分析,关于其研究刚刚开始。

本文介绍了最近发生在西班牙的、由于地基失效导致的海上工程内部损坏的两个例子(马拉加,2004 年 7 月,巴塞罗那,2007 年 1 月),分析了其成因。

关键词　地基　海洋建筑物　破坏　海岸线　西班牙

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1 Introduction

Analysing maritime constructions with differentiated techniques is a fairly common situation in engineering schools or faculties. Wave energy is the predominant action on breakwaters without taking the ground supporting these enormous solid blocks into account. Soil, loads and fills in inner constructions, laying less stress on the wake effects (screw waves), internal disturbance, the tidal range or residual wave action.

Training centres on wave action and breakwaters for a specific type (shelter) and geotechnics and quays for another (transferring cargo and passengers). This separation is also seen in working life and has repercussions on both design and the different construction phases of maritime works.

Another fact must be added. The environment where structures are built in the sea is not seen, it is submerged and the reference level changes because of the oscillation of the free surface and its recognition is a point thing, since the number of boreholes or of data taken is small in comparison with the length of its alignment.

In following the Maritime Works Recommendations, "Geotechnical Recommendations for the Design of Maritime and Harbour Works", Ministry of Public Works, 1995-2005, its chapter 2.5 explains ground reconnaissance Programming, whilst table 2.12.3 specifies the number of investigation points in reconnaissance work at a low and minimum level.

Both breakwaters and quays are linear constructions, and a sampling point is set every 50m in a low case and every 100m for the minimum level. If, to these figures, are added the dimensions of some outer constructions on the Spanish coastline, Langosteira (Corunna) with a 3334m rubble mound structure, Cape Torres in Gijón with 3834m, Barcelona with 7319m or Algeciras with a length of 2020m, we may raise doubts on the scarcity of samples and boreholes characterizing the ground supporting maritime constructions.

Another singular aspect it is wished to raise in this introduction is how spectacular the failure proves, and it may be thought that the designs, construction techniques and way in which the constructions are built may be precarious. Together with the Japanese, Spanish technique in Maritime Engineering is deemed to be a world pioneer both on a scientific and academic and professional level.

However, constructions built over the last ten years, reaching close to one billion euros in investment, show few failures out of a total of more than one hundred breakwaters and quays, a very low percentage, despite how much attention is drawn and the repercussion such bears with it in the engineering world.

Finally, prior to dealing with the two cases, maritime works are not fully stable until entirely concluded which is why an analysis is required as defined in the Recommendations for Maritime Works, Actions in Designing Maritime and Harbour Works, Rom 0.2/90.

Epigraph 2.1.3

"For designing structures included in the sphere of application of these recommendations, all work phases, "sub phases" and hypotheses possible will be taken into account, provided they affect sizing, proceeding to the itemised and individualised analysis of each structure in its entirety and of each of the resistant elements in each of the phases".

Epigraph 2.1.4

The Designer shall set the duration of each of the project's phases affecting sizing, in view of its special meaning in the evaluation of:

· Levels of the structure's safety to factors or states depending on time: fatigue, corrosion, marine adherences, long term ultimate ground bearing capacity

· Forces and levels of probability associated to return periods and limit states

· The project's economic feasibility and possibility of future development

If, during the construction phase, the performance terms or construction processes provided for in the Project are altered, the effects of those alterations on design forces and, therefore, on sizing, shall be taken into account.

Because of all these circumstances, the analysis is complex and this article suggests it be reflected on and discussed.

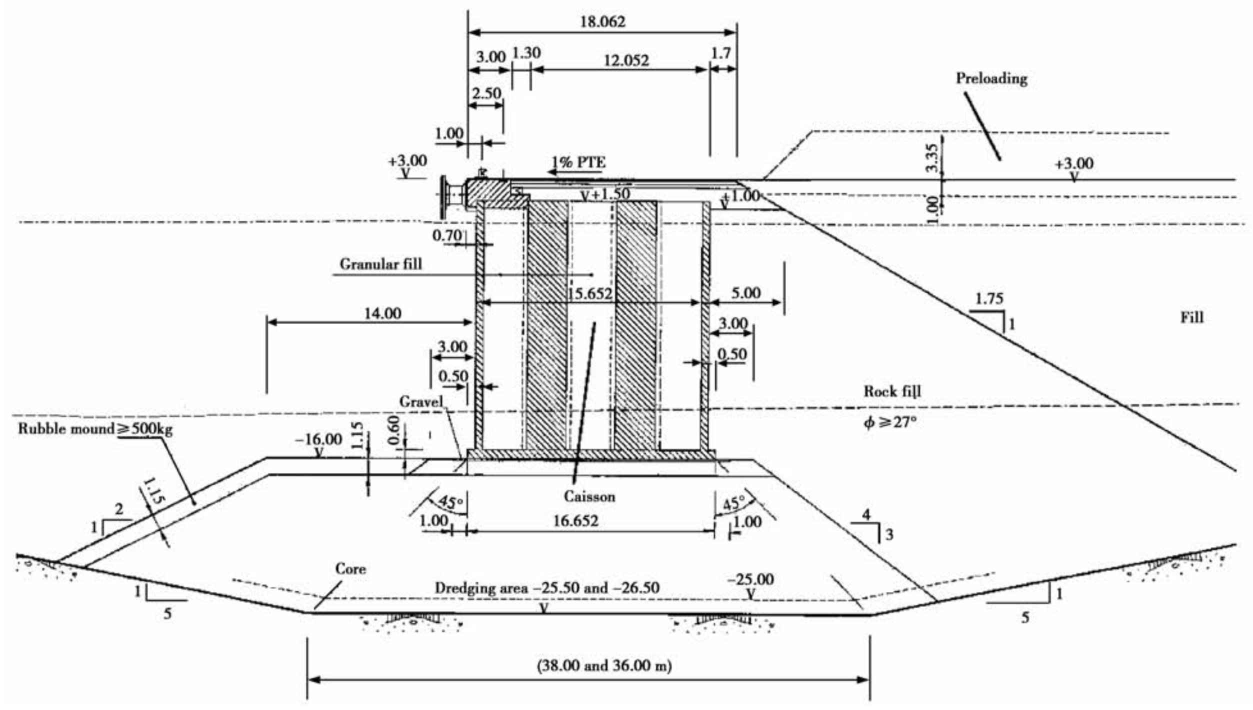

Fig. 1 Standard cross section of the Malaga quay

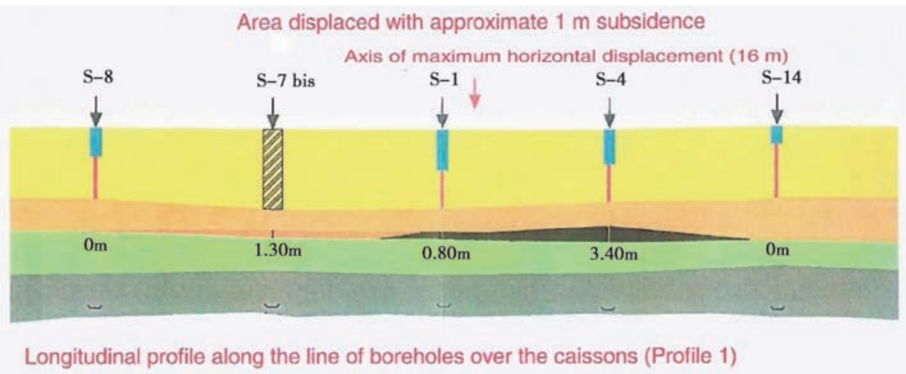

Fig. 2 Longitudinal profiles along the quay's alignment

2 Study cases

2.1 Malaga harbour container terminal

The type of structure of the quay subject to reflection is a gravity monolith construction arranged on a foundation banquette with a thickness of over eight metres built after dredging from ground level, at - 15.00m to the approximate bathymetric level of - 22.00m. The material dredged is silty mud with an internal angle of friction around ten degrees. The dredging slope was 5/1 on the exposed side and 7/1 on the inner side.

In order to operate the Terminal on the concession system, the fill was consolidated by a preloading system with three metres height at the rear of the civil land side work. The quay's standard cross section and the geotechnical profile (boreholes) are shown in figures 1 and 2.

The first part of the construction was finished in July, 2004and it commenced operating, with ground improvement and consolidation continuing in the Terminal's second construction phase.

As a consequence of an excessive preloading in level and weight (over 3.00m), a construction programme insensitive to the structure's notable settlement, for reasons of operation as a concession, and a film of mud in the central section of the construction between competent ground levels, undetected in the geotechnical reconnaissance phase, the central core of five caissons

Fig. 3 Malaga quay in the construction phase

Fig. 4 Deep central core sliding phase

slid outwards causing the quay's cope line to collapse. Without doubt, the ground's sensitivity to instantaneous loads, the high short term transmission of stresses, the possibly insufficient dredging or the potential scarcity of the rock fill banquette combined with very rapid construction, exceeding two hundred linear metres a month, are some of the reasons set forth in the explanation to the system's overall stability problem and its deep sliding.

Both static and dynamic numerical models justified the break lines because of the presence of the intermediate layer of mud in the competent strata. The ground's response was quick and the component system failed causing an ultimate sliding state because of overall stability and a limit service state that led to an operating phase which was delayed more than twelve months with the

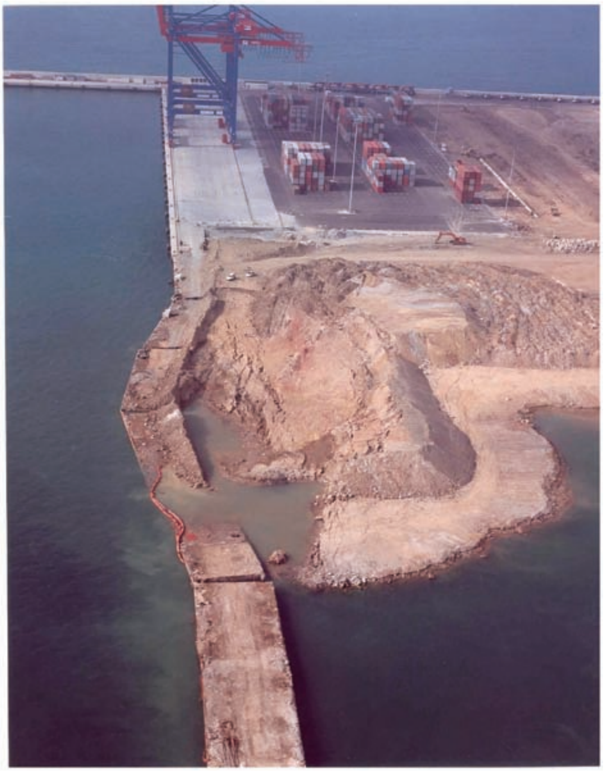

Fig. 5 Collapse of the second phase of the Terminal. East-West aerial view

Fig. 6 West-East aerial view

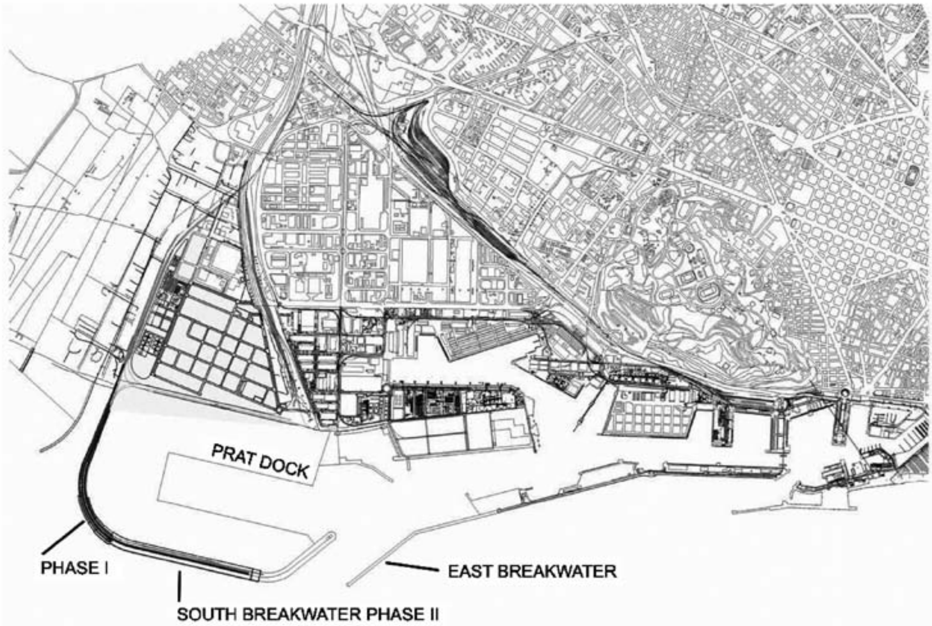

Fig. 7 Barcelona Harbour extension projects, 2005 - 2015

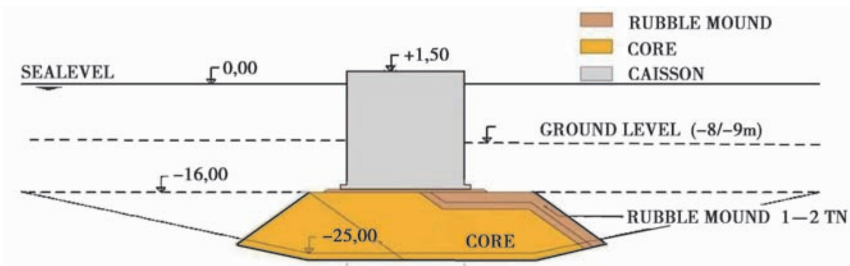

Fig. 8 Typical prat quay cross section, first phase (breakwater behaviour)

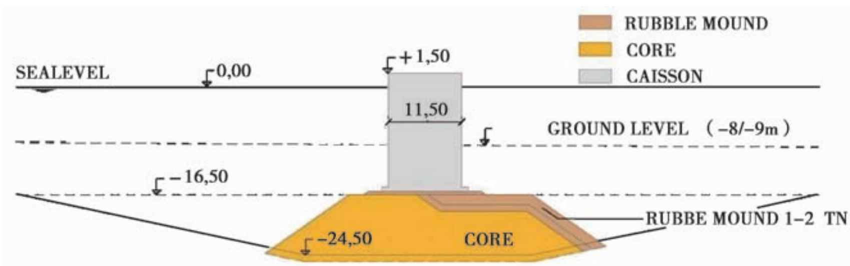

Fig. 9 Typical prat quay cross section, second phase (dock behaviour)

demolition and replacement of the structural elements (caissons) and foundations (cleaning, dredging, banquette pouring, regulating and levelling). The following figures are sufficiently illustrative of the problems described.

2.2 Case of the prat quay in barcelona

The Prat quay is a 1500metres long inner construction which was expected to come into service by the beginning of 2008. It is protected by the south extension to the Barcelona breakwater in its sections I and Ⅱ. Divided into two parts, Prat I is built after mud dredging from level −16.00m to −25.00m; a 9.00m thick rock fill banquette and a four cell caisson suitably levelled on the granular foundations at level −16.00m.

It works like a protection defence in the construction phase whilst at the same time, the outer breakwater works are advancing.

The second phase, now sheltered by the extension's

Fig. 10 State of Prat Quay after the collapse

Fig. 11 State of the caissons after the quay slid

Fig. 12 State of the caissons after the quay slid

sloping breakwater, is therefore built with a caisson (11.50m width), on a banquette at level −16.50m and 8.00m thick, after dredging in incoherent material to level −24.00m.

After caisson building, the quay is completed in its two phases with rubble mound at the rear, hydraulic fill and a provisional pavement, controlling differential settling prior to its operation.

On examining the design and the different construction phases, certain peculiarities can be seen in these works.

· The first phase works like a breakwater because the caisson is subjected to dynamic wave actions through not being sheltered by the extension works. This justifies the greater caisson width.

· The second phase is now an inner construction with a gravity structure, the width of which is required by the calculation for ultimate limit and service states

· Both constructions are put out to tender separately and with a slight time lag

· Transformation from breakwater to quay, the fill phase, consolidation and paving are also put out to tender separately

· The caisson and fill works are built by different companies

· Their Site Managers are also different

· Fills are made quickly because of operation requirements. The Terminal has now been handed over to the operator

· Fills are hydraulic in nature with scarce geotechnical properties

· These fills are made from the land seawards, i.e., from the yard area towards the caisson, increasing the water level inside the lake formed between advance levees

· Drain spillways were not provided for

· The rear rubble mound was not arranged in the caisson's rear wall in the first phase of turning the breakwater construction into a quay. Thrusts on the monolithic structure are different to the design's and not provided for

· The caisson was built up with impermeable clay cores, turning the construction into a dam, with thrusts far higher than the calculation's

· These situations did not address the articles of the ROM 0.2 with respect to the design and construction phases and sub-phases

· The medium is subjected to alternating loads deriving from dynamic wave forces

· The balance of effective and neutral stresses may cause ground liquefaction and siphoning

In this situation, with such a precarious mechanism, a slight disturbance (environmental, geotechnical or structural) made the quay slide causing it to collapse on 1 January, 2007.

After debris removal, blasting and caisson refloating, repair works were undertaken during 2008 and 2009, and the Terminal may come into service at the beginning of 2010.

3 Conclusions

In the light of the reflections and analyses made of both ground-structure interaction problems (Malaga and Barcelona) in a marine environment subjected to alternating stresses, the following ideas may be set as conclusions.

(1) The choice of the type of structure displays an essential component in relation to the ground supporting it. The use of gravity elements in this ground would have required treatment improving or consolidating same in order to obtain equivalent higher strength geotechnical parameters

(2) Dredging to a certain level, replacing soft ground with granular elements, preloading, the use of gravel columns, replacement and vibro-floatation or vibro-replacement are some of the techniques in use for this type of ground-structure interaction

(3) The use of elements such as piles, sheet-piles or enclosures could have been considered in the quay's design

(4) The ground always has a response. Loading it too quickly may cause short term stability problems

(5) Construction works should not have to be built under pressure from the administrative concession. Their rate of construction is irrespective of the operation's

(6) Rear rubble mound is an essential element in gravity quay stability. It is recommended to be granular with angles of internal friction exceeding 37 degrees

(7) An inner construction is interdependent. The containment wall and yard fills cannot be addressed separately

(8) Water removal during filling in the work phase should be provided for and drain spillways provided

(9) All design phases and sub-phases should be analysed in the justifying calculations and not just the ultimate limit and service states

(10) The repair of a failure in a maritime construction is more difficult, costly and requires more work time than building a new structure. Demolition and debris removal slow down and delay any type of work in the sea

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